

# Ground Control Testbed for Space Station Freedom Robot Manipulators

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## Abstract

The Robotic Systems Technology Branch at the NASA/Johnson Space Center has completed a baseline ground control testbed for use in developing and evaluating technology for Space Station Freedom (SSF) Robotic Tasks. The focus of the first phase of this work has been addressing the effects of significant ground to orbit time delays on operations. This testbed uses a predictive display to enable virtual real-time control of a remote robot. The operator commands a graphical kinematic manipulator through hand controllers or automated sequences which in turn drive the actual manipulator after a user defined delay. The predictive display provides artificial camera views that enable the operator to measure clearances not available in actual camera views. A delayed camera control interface, and a robot verification display are also available. All testbed components are connected in a distributed processing environment. This paper describes the ground control testbed architecture and technology utilized to address the time delays.

## 1. Introduction

Ground control of robot manipulators has been proposed for use during the Space Station Freedom's (SSF) Man Tended Configuration. During this period crew personnel will only visit SSF, but two to three extra-vehicular robot manipulators are currently scheduled to be on board and operational. These ground controlled manipulators would perform periodic inspections for micrometeorite damage, necessary maintenance and possibly prepare the station to meet specific mission requirements prior to crew arrival.

Ground control of teleoperated manipulators introduces a large time delay, anywhere from 3 to 6 seconds one way, that previously has not been a factor in the operation of the only existing space based robot, the shuttle manipulator system. Using operational procedures equivalent to the shuttle's, with this time delay, will result in increased task time, safety concerns, and may even prohibit task completion. Clearly, additional operator aids are required.

The operational aids provided by the JSC testbed include predictive and verification displays, artificial camera views, and force/torque compliance. Previous work at the California Institute of Technology, Jet Propulsion Laboratory (JPL) has included the development and testing of similar aids for a peg-in-hole task [1]. The JPL work focused on displays that were globally calibrated. The JSC testbed addresses local calibration for situations where high accuracy is needed, for example, payload insertion. In addition, experiments performed with the JSC testbed represent the closest approximation to planned SSF activities to date [2]. The operator's console adheres to the current design for the JSC Space Station Control Console (SSCC), and the contact interfaces for both the manipulator and the tested payload conform to the NASA Robotic System Interface Standards [3]. Preliminary testing has indicated that the operational aids provided by the JSC testbed are useful in compensating for ground based time delays.

## 2. System Architecture

The system architecture for the Ground Control Testbed (GCT) is centered around a distributed processing environment which uses an Ethernet-TCP/IP network for connecting the various subsystem segments. The testbed computing base uses three PC/DOS computers and one Silicon Graphics (SG)/UNIX machine. The SG machine executes the majority of the ground control system software, while the PC's function as interfaces to external hardware. A functional block diagram of the system is shown in figure 1. A description of this system's major components: network data distribution, ground control operator workstation, and robot workcell subsystems, is given in the following sections.

## 3. Network Data Distribution

The distributed communications software which the GCT utilizes is the TeleRobotics Interconnection Protocol (TelRIP) [4]. TelRIP is a socket based data exchange mechanism developed at Rice University which allows multiple processes and processors to communicate in a common environment. Processes communicate through routers (TelRIP applications which manage the flow of data between processes). Each application process contains a TelRIP stub which maintains the socket connection with one router. Numerous and even remote interconnections may be created over an Ethernet-TCP/IP network as multiple routers can maintain connections to each other as well as local processes.

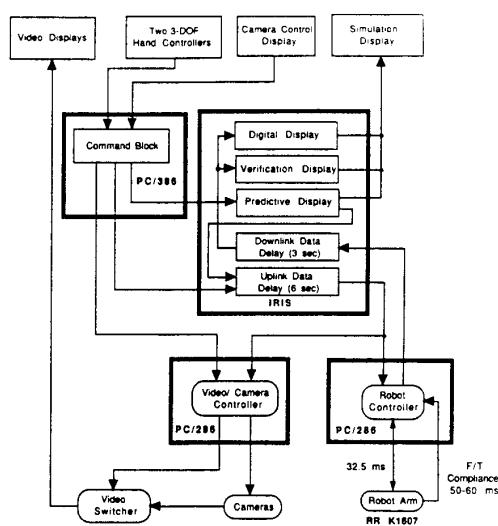


Fig. 1 Functional block diagram

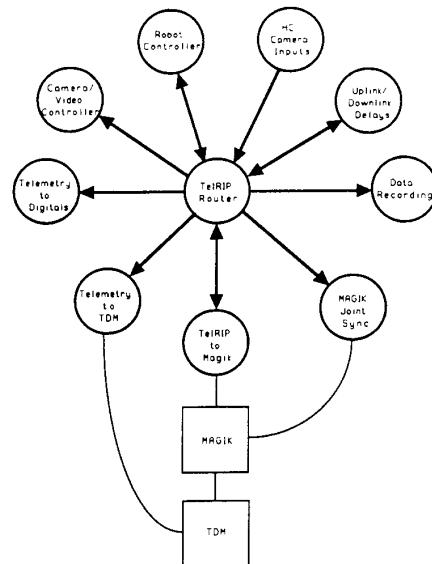


Fig. 2 TelRIP connection diagram

TelRIP contains a set of user procedure calls which may be linked with application specific software. TelRIP also maintains a set of data objects which provide a generic capability for robotic systems. In addition, users may create their own data objects when the standard objects are not sufficient. A connection diagram for the GCT is shown in Figure 2. For the testbed a single router is used to connect nine processes on four separate processors. This configuration provides the most efficient data transfer for a local connection. If the throughput of a single router were

exceeded, point-to-point connections maintained external to the SG workstation, or remote connections with heavier external network traffic established, a multi-router network configuration would be utilized.

#### 4. Ground Control Operator Workstation

The Ground control operator workstation, shown in figure 3, represents the best approximation to date of the planned SSCC environment. One large and four small video monitors are available to display various workcell camera views that are routed through a PC controlled video switcher. A separate 386 PC provides controls and displays for the cameras and various robot functions. Two 3 Degree of Freedom (DOF) handcontrollers (HC) enable the operator to drive the point of resolution (POR) of the robot. The SG workstation generates the robotic simulation and graphical displays and provides telemetry data to the operator. In addition, the SG performs the data routing, data delays and data recording for the system.



Fig 3. Ground control operator workstation

#### 5.0 Simulated Robot Environment

The graphical simulation environment of the robotic workcell testbed utilizes three existing software modules developed at JSC: the Solid Surface Modeler (SSM)[5], the Tree Display Manager (TDM)[6], and the Manipulator Analysis: Graphics/Interactive/Kinematics (MAGIK) simulator[7]. Four TelRIP processes were developed to integrate the graphical environment in with the distributed testbed environment. Two additional TelRIP processes provide the simulated communication delay and data recording functions.

The simulation consists of two robot models and the workcell models built using SSM. The first robot is a solid model graphic and is driven in real-time by MAGIK. MAGIK generates motion commands to this robot and the Robotics Research (RR) 1607 manipulator either from HC data or internally stored motion trajectories. The second simulated robot is an identical wire-frame model, and its position is updated from a TelRIP process receiving delayed telemetry joint angles. Using this approach, the operator can drive in real-time a predictive robot while also viewing a verification model which shows the robot's fed back state with delays. Figure 4a gives an example of the predictive and verification models that correspond to the actual RR1607 seen in figure 4b. In addition to the graphical views, digital robot state information is displayed on the operator console which corresponds to the predictive and verification displays of the simulation.

A TelRIP process which ensures that the predictive MAGIK robot maintains the same joint configuration as the actual robot was developed since the inverse kinematic algorithm for the RR1607 is proprietary, non-unique, and currently unavailable. MAGIK's inverse kinematic model, based on rate minimization and joint limit avoidance, produces slightly different joint angles for the identical Cartesian command. To keep the predictive robot synchronized with the RR1607, the TelRIP process periodically updates MAGIK's joint position with the RR1607's values.

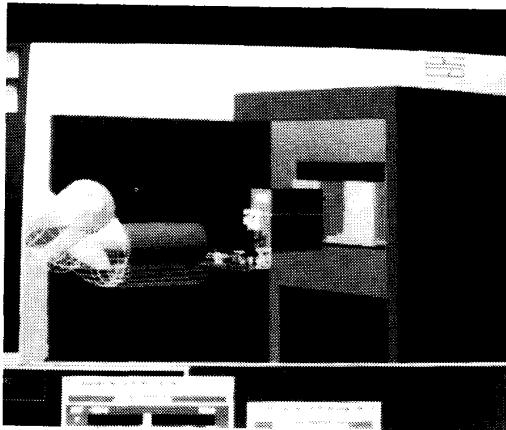


Fig. 4a Predictive and verification display

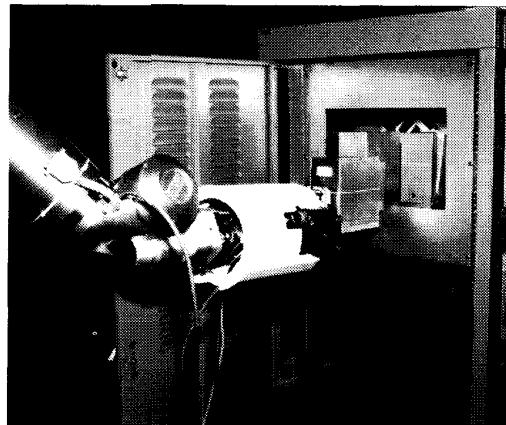


Fig. 4b Actual workcell

To model the delays estimated for the SSCC to SSF communications environment a TelRIP process provides separate command uplink and telemetry downlink delays. Due to the difficulty in producing a real-time video delay in the required development cycle, the estimated video delay was added into the command uplink delay and subtracted from the telemetry downlink delay to produce the same overall round-trip delays for both loops. Currently the delay routine adds a fixed delay since there was no quantitative data to indicate how the actual delays might vary over time.

To measure the performance of the test subjects a TelRIP data recorder was built to record any data objects being sent through the router. The features of this data recorder include: data object selection, data scaling and bit unpacking, individual recording rate specification, sub-task time recording, and file storage specification.

### 5.1 Workcell Calibration

The dimensional accuracy of the predictive display relative to the real world is dependent on several factors: solid modelling, camera modelling, structural flexibility of the modelled environment, and robot position accuracy. The CAD solid models and camera models will be well documented for SSF and maintaining an accurate database will not be difficult, but structural flexibility and robot accuracy are not as easily accommodated. The SSF is a flexible structure, and deflections will exist between a truss camera and a work site several meters away. This will result in different views from the predictive displays cameras and the actual cameras. A similar difference in views results from the accuracy of the SSF manipulators. For example, the Space Station Remote Manipulator System (SSRMS) is expected to have a positioning accuracy similar to the Shuttle's

Remote Manipulators 5 cm accuracy[8]. When the SPDM is performing a task while attached to the SSRMS, the SPDM's end effector's true position can be off by as much as 5 cm plus its own accuracy. This difference is significantly larger than many operational tolerances associated with grappling objects and inserting payloads[3].

The value of the predictive display lies in its accuracy. Currently, the predictive display is calibrated manually whenever high accuracy is required. For instance, just prior to grappling a payload interface, the differences between the predictive end effector camera view and the real view are minimized by moving the base of the predictive robot model. The position of the robot base is no longer accurate, but this is not critical since it is not near any other objects and will also not move while the end effector is in motion. The wire frame verification robot model shares its base frame with the predictive robot and is, therefore, also calibrated during the same process.

In addition to re-creating actual camera views, the predictive display offers the advantage of viewing objects from any location and orientation. Figure 5 shows an artificial view of a payload insertion from a few inches above. Two parallel lines are positioned at the height of the receptacle and serve as a lateral alignment aid for the payload. This portion of the predictive display's graphical model is calibrated against the world at grappling time and just prior to payload insertion, ensuring that the artificial view accurately models the relative distance between payload and receptacle. This technique was useful in providing position cues that are often difficult to extract from either a simulated or actual camera view. In this case, the cues were very helpful in laterally aligning the payload to within 0.3 cm to permit insertion.

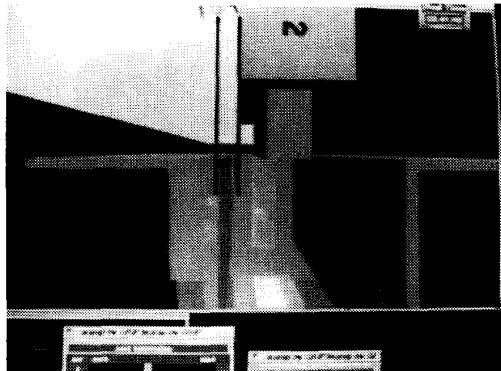


Fig. 5 Artificial view

## 6. Robotics Research 1607

The Robotics Research(RR) 1607 was chosen for use with this test bed because of its similarity to the proposed SSF Special Purpose Dexterous Manipulator (SPDM) [2]. Both Manipulators have seven DOFs and both have a horizontal reach capability of approximately 2 meters when augmented with grippers. In addition the RR1607 has been augmented with an active force/torque compliance system similar to the one planned for the SPDM.

The RR1607 controller is based on an open architecture multi-processor design. The baseline user interface for this controller that permits the operator to teach the robot points for later execution was

replaced by a MAT286 Single Board Computer. The MAT286 provides a flexible PC interface to the RR1607's motion controller and servo controller processors. This interface, written in C, consists of a set of functions that initialize the robot, command Cartesian and joint moves, acquire feedback data, monitor the RR1607 processors, and halt or shut down the system when necessary.

For the GCT application, the RR1607 is commanded at the motion controller level. The Mat286 receives either End Effector (EE) rate or position commands from the GCT workstation, combines this data with output from a local force/torque compliance algorithm, and then sends a rate command to the robot in EE coordinates. The current position of the EE is returned by the motion controller, is used to calculate the next rate command and is also sent to the workstation telemetry display. In addition the program running on the MAT286 performs housekeeping functions, including rate limiting, and input scaling.

### 6.1 Force/Torque Compliance

The RR1607 was previously augmented with a force/torque compliance capability as part of a Shuttle Remote Manipulator System Study [9]. A six axis JR3 force/torque sensor is attached to the manipulator's tool plate and reads all the forces and torques experienced by the end effector and payload. The readings are processed by the JR3's controller and then sent to the MAT286 over a RS232 communications line. Each axis is handled individually. The appropriate force or torque is multiplied by an experimentally determined gain and then subtracted from the handcontroller rate command for that axis.

Using this technique, an operator may input a single axis command to perform a constrained motion. In the case of a hinged door, the operator commands manipulator's end effector to pull the door straight back in the X direction, and the compliance algorithm commands both Y and Yaw motion to null out forces in each axis. The result is a smooth door opening with the robot, in a sense, following the door handle.

## 7.0 Future Enhancements

The most obvious enhancement for the ground control workstation is the capability to actually perform automatic calibration between the workcell and the simulation. One technology which can add this functionality, Operator Coached Machine Vision, is being developed at the Jet Propulsion Lab and will be integrated this fiscal year. Other simpler methods to accomplish this function are also being considered since the calibration task is well structured for relatively simple machine vision algorithms.

To increase the fidelity of the testbed, a 30 frame/second video delay capability is being added. This delay will be variable from zero to several seconds and will eventually be able to multiplex up to four inputs at once onto one video screen.

Intelligent displays which continuously monitor data and provide high level messages to an operator are being developed. The target applications of this technology will be in robot and communication system state and health monitoring. The current testbed monitors for robot joint position and rate limit violations. Another upgrade will be to convert all interactive control displays to X-windows for greater portability.

## 8. Acknowledgements

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